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NEUTRON-CAPTURE ORIGIN FOR HEAVY ELEMENTS

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Neutron-Capture Origin for Heavy Elements

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--- If gold ruste, what shall iren do ? (Chauser)

Abstract: It is believed that most of the heavy isotopes naturally-occurring in the solar system were produced in the interiors of stars by way of the neutron capture processes. The following is an introductory summary of an alchemy by neutrons in the stellar interiors. Much remains to be worked out despite the remarkable progress this filed of study has made in the past.

1.Introduction

The total number of naturally-occurring stable (or quasi-stable) nuclides in the solar system amounts to 286. Among them, some 20 species including $^{235,238}U$ are radioactive with the long half-lives and have survived the age of the solar system of ca. 4.5 billion years. [The existence of ^{234}U (half-life: $2.5x10^5$yr) is due to the decay from ^{238}U.] It is easy to imagine, in return, that many shorter-lived isotopes were temporarily present at the time of the formation of the solar system. Indeed, the search for the possible traces of such isotopes in meteorites is of extreme importance.

At the same time, the clarification of the conditions under which the solar material was formed, having led to the now-observed abundance ratios as shown in Fig.1, remains as one of the most interesting subjects in (nuclear) astrophysics. In the following, we focus on the synthesis of the heavy elements (i.e. the elements heavier than iron).

It has been realized from early days that the light elements are synthesized in the interiors of stars and that the heavy elements are enhanced in certain stars when compared with the solar system abundances. In early 1950's, the Tc line was discovered in the atmosphere of red-giant stars, and it became clear that the heavy elements could also be produced in the interior of stars and brought up to the stellar surface within relatively short periods. [Any of the Tc isotopes has short half-life such that no Tc can exist in the solar system. The observed Tc is most likely ^{99}Tc.]

In 1957, Burbidge, Burbidge, Fowler and Holye (B^2FH) showed that most heavy isotopes could be synthesized by way of the neutron capture, the idea still being the basis of the current studies of the heavy-element nucleosynthesis. Along with the developments of nuclear physics during the next ca. 40 years, we now know as to which conditions (temperature, neutron density etc.) are suitable for explaining the heavy-element abundances in the solar system.

On the other hand, it is natural to expect that the matter which participated in the solar system formation was a result of the evolution of the numerous stars that had existed and died in our Galaxy. There have been many efforts to find out in which stars and in which evolutionary stages the above-obtained conditions are fulfilled, but no consistent and quantitative solutions have been reached to date.

The following is merely an introduction to the nucleosynthesis of the heavy nuclei via the neutron capture, and readers are referred to the articles cited later at the end. [Because this article is meant for non-experts, the quotation of the original references are to a great deal avoided.]

2. Slow (s-) and rapid (r-) capture processes of neutrons

The n(eutron)-capture rate in question is given by

$$\lambda_n = n_n v_T \langle\sigma\rangle, \qquad (1)$$

where n_n is the neutron number density, v_T is the neutron thermal velocity, while $\langle\sigma\rangle$ is the Maxwellian averaged (around v_T) radiative n-capture cross section which depends on the property of the nucleus of interest. The product $v_T\langle\sigma\rangle$ in heavy nuclei is about 10^{-15}-10^{-17} cm^3sec^{-1}, and is almost independent of the temperature T.

With the aid of Fig.2a, let us consider the n-capture, assuming a heavy nuclear species ^{56}Fe embedded in the neutron sea. Since $^{56,57,58}Fe$ are stable, ^{56}Fe will sooner or later capture neutrons to become ^{59}Fe which has a β-decay half-life of 45 days. According to B^2FH, let us now consider the extreme cases of the neutron density n_n. First, we consider the case of low neutron density and take $n_n \sim 10^6$ cm^{-3} as an example. If we adopt $v_T\langle\sigma\rangle \sim 3\times10^{-18}$ for ^{59}Fe, we have from eq.(1) $\lambda_n \sim 3\times10^{-12}$ sec^{-1}. Namely, it will take ca. 10000 years for ^{59}Fe to capture a neutron, and ^{59}Fe will meanwhile beta-decay to ^{59}Co instead. In a similar way, the synthesis will proceed on a zigzag path along the stability line. This kind of synthesis is called as the s(low)-process since the n-captures are slower than the β-decays.

If we assume $n_n \sim 10^{24}$ cm^{-3} as an example for the case of high neutron density, the n-captures occur much faster than β-decays, so that ^{59}Fe will successively add neutrons to become ^{60}Fe, ^{61}Fe and so on. However, when the neutron number becomes the magic number 50, namely at ^{76}Fe, the n-capture becomes very hard to occur, so that ^{76}Fe undergoes the β-decay to ^{76}Co with an estimated half-life of ca. 1 ms. In a similar manner, the synthesis proceeds along the path in the region of neutron-rich nuclei as shown on the righthand-side of Fig.2a. This is the r(apid)-process. Once the neutrons disappear for some reasons to terminate the synthesis, the neutron-rich nuclei synthesized till then β-decay, resulting in a cascade toward the region of stable nuclei.

Figure 2b shows the situation at a heavier mass region. It shows that ^{154}Gd and ^{160}Dy can be made by the s-process, ^{160}Gd by the r-process, and $^{155-158}$Gd, ^{159}Tb, $^{161-164}$Dy by both processes. On the other hand, some neutron-deficient nuclei such as ^{156,158}Dy can be produced neither by the s-process nor by the r-process. The mechanism responsible for the formation of such nuclei is generally called as the p-process.

Figure 3 shows the solar abundance curve qualitatively decomposed according to the above three processes. As we describe later, the peaks at the mass numbers A = 90, 138 and 208 for the s-process and at A = 80, 130 and 194 for the r-process correspond to the neutron magic numbers 50, 82 and 126, respectively.

The repetition of the n-captures and the β-decays increases the mass number and the atomic number. However, the s-process cannot produce stable elements heavier than ^{210}Bi, reason being the fast α-decay of ^{210}Po. On the other hand, the r-process can proceed to very heavy nuclei until it reaches the region of fissioning nuclei, thus producing the progenitors for ^{235,238}U and ^{232}Th.

The abundances of p-process nuclei are generally small. Since the number of p-process nuclear species is limited, and since the n-capture does not directly participate, we will disregard the p-process in the following.

3. The s-process

For an easy understanding of the r-process, we had better start with explaining the s-process.

3.1. Semi-empirical analysis of the abundance curve

For convenience, let us first assume that the s-process path does not have any branching points. Namely, we assume that only one stable (or quasi-stable) nuclide per a given mass number A participates in the s-process. Then, the time-variation of the relative abundance N_A follows from eq.(1)

$$dN_A/dt = + n_n v_T \langle\sigma\rangle_{A-1} N_{A-1} - n_n v_T \langle\sigma\rangle N_A. \tag{2}$$

If the flow is steady, that is, if there are enough seed nuclei and neutrons over a long-enough time period, we have $dN_A/dt=0$ so that

$$\langle\sigma\rangle_{A-1} N_{A-1} = \langle\sigma\rangle_A N_A = \text{const.} \tag{3}$$

Since $\langle\sigma\rangle_A$ is generally larger for heavier nuclei, N_A decreases with A. If the neutron number is one of the magic numbers 50, 82 and 126, however, the n-capture is difficult (i.e. small $\langle\sigma\rangle_A$), and the flow gets stuck there, leading to the three peaks in the abundance curve seen in Fig.3. Because of this, many s-process studies have been devoted to the analysis of the product σN. Unfortunately, eq.(3) only holds relatively well in a narrow range of A. Actually, the curve drawn in Fig.4 has been obtained by assuming an appropriate (exponential) distribution of the neutron flux $\tau=\int n_n v_T dt$.

If we investigate the nuclei along the s-process path more carefully, furthermore, one encounters the cases in which the very assumption of no-branching does not hold. First of all, many odd-odd nuclei undergo the β decays to both $Z \to Z\pm1$ directions. Depending on n_n, in addition, the n-capture may well compete with the β-decay. Furthermore, the β-decay generally becomes faster at high temperatures, so that, in marginal cases, even the terrestrially-stable isotope can β-decay faster than the n-capture.

As we already mentioned, many nuclear species can be produced by the s- and r- processes. The evaluation of the s-process contribution to the abundances of those nuclei can only be made by way of interpolation such as shown in Fig. 4. The consideration of the so-called "branching problem" above mentioned is inevitable in improving the precision by such an interpolation. More importantly, such an analysis often gives a hint as to which astrophysical conditions are appropriate for explaining the solar abundances. If we take $n_n = 10^8$ cm^{-3}, ^{160}Tb in Fig. 2b for instance undergoes the neutron capture with a time scale of ca. 100 days, which is comparable to its β-decay half-life of 72 days. If this competition (branching) occurs, then the abundance ratio ^{160}Dy/^{161}Dy becomes smaller. If we assume a temperature of 3×10^8 K, however, the ^{160}Tb β-decay half-life could be as short as half a day so that there would be no branching.

There are many interesting studies of the branching problem in the last few years. Because of the space limitation, we merely present here the s-process conditions that are generally thought to be appropriate for explaining the solar abundances: The temperature T ~ 3×10^8 K, the neutron number density $n_n \sim 10^8$ cm^{-3} and the exponential distribution of the neutron flux τ over a few hundred years.

3.2. Stellar evolution and the s-process

The vast majority of the stars with the masses of ca. 0.1 - 100 $M_\odot$ ($M_\odot$: the solar mass) start their evolution with the core H-burning. This is done by the so-called p-p-chain in the stars lighter than ~ 2 $M_\odot$ and by the so-called CNO cycle in the heavier stars. The stars spend most of their life in this phase as observed in great deal as the main-sequence stars. [The main-sequence phase of the light stars such as the Sun continues over as long a period as the age of the Galaxy. Fortunately, the Sun has spend only the one third of this phase.]

After the main sequence, the stars heavier than ca. 0.5 $M_\odot$ undergo the core He-burning to become the giant stars. The following evolution depends on the stellar mass. Roughly speaking, a star lighter than ca. 7 $M_\odot$ eventually ejects the planetary nebula, leaving a white dwarf, and a star heavier than ca. 10 $M_\odot$ experiences the supernova explosion, leaving either a neutron star or black hole.

The s-process needs neutrons to begin with. A candidate for the neutron production can be found at the core He-burning phase of heavy ($\gtrsim$ 10 $M_\odot$) stars. The neutrons are produced by the chain reaction on ^{14}N produced in the CNO cycle i.e. $^{14}N(\alpha,\gamma)^{18}F(\beta)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$. It is worthy noting that this reaction is very temperature-sensitive and requires temperatures in excess of $3x10^8$ K to be effective. This value for the temperature just coincides with the value inferred from the semi-empirical analyses of the solar abundances. According to the numerical calculations, however, the s-process in this scenario can not produce enough heavy nuclei with the mass numbers A $\gtrsim$ 100 and thus has a difficulty in the comparison with the solar abundance curve.

The most promising site for the s-process can be found in the shell He-burning phase in the intermediate mass (2-7 $M_\odot$) stars. After the core He-burning, the He-burning continues at the peripheral narrow shell and produces the recurrent thermal pulses and a convective shell. The convection fetches the ^{14}N from the outer H-burning zone. At the bottom of the convective shell, where the temperature is as high as $3x10^8$K, again the chain reaction through $^{22}Ne(\alpha,n)^{25}Mg$ produces neutrons for the s-process. The virtue of this model is that the position of the matter each pulse irradiates shifts bit by bit as the C-O core mass increases by each pulse. If a sufficient number of pulses occur, the situation is equivalent to assume that the matter is bombarded by the exponentially-distributed neutron flux τ in accordance with the finding from the semi-empirical analysis. Indeed, the s-process at this phase of 3-5 $M_{\odot}$ stars is seemingly appropriate for explaining the solar abundance curve.

On the other hand, it is important to investigate the elemental abundances in stars aside from those in the solar system in order to know the real occurring of the s-process during the stellar evolution. [It is generally difficult to observe isotopic abundances in stars.] For instance, there have been some attempt to explain the Tc observed in red giants within the thermal-pulse model described above. Each thermal pulse disappears after ca, 20 years, and it takes ca. 30000 years to have the next pulse appear. The outer convective envelope goes down meanwhile and dredges up a part of the s-process product nuclei, which then may be observed at the stellar surface. Another interesting cases concern the so-called Wolf-Rayet stars, which have the mass of ca. 30-100 $M_{\odot}$. In these stars, the envelope are removed in such a way that the advanced stages of stellar evolution can be observed directly. In reflecting this merit, there have been several s-process studies for those stars.

4. The r-process

The subtraction of the s-process contributions determined from the semi-empirical analysis from the observed solar abundances leaves the "observed" r-process abundances. Such an example is shown in Fig.5.

4.1. Semi-empirical analysis of the abundance curve

For simplicity again, we first assume that the r-process occurs without branchings. Namely, we assume that, for a given atomic number Z, all but one β-unstable nuclei undergo the n-capture much faster than the β-decay. Then, the abundance ratio N_Z is determined by the β decay in contrast to the case of the s-process, and its time variation is given by

$$dN_Z/dt = + \lambda_{\beta,Z-1} N_{Z-1} - \lambda_{\beta,Z} N_Z, \quad (4)$$

where $\lambda_{\beta,Z}$ is the β-decay rate of the nucleus that cannot effectively capture the neutron. For a steady flow, therefore,

$$\lambda_{\beta,Z-1} N_{Z-1} = \lambda_{\beta,Z} N_Z = \text{const.}. \quad (5)$$

In general, the farer the nucleus from the region of β-stability, the easier the n-capture, and the contour lines of the n-capture rates are roughly parallel to the line of β-stability. As the path hits the neutron magic number, however, the n-capture becomes difficult to occur, which results in the path bending toward the increasing Z for a while (see Fig. 6). Since the β-decay rate contours are also roughly parallel to the β-stability line, the flow is stuck at the top of this bending path. From this, one can understand that the three peaks in Fig.3 correspond to the neutron magic numbers N = 50, 82 and 126.

In the above approximation, the abundance curve is continuous in Z but not in A. A better approximation can be obtained by assuming the equilibrium between the capture and emission (due to photo-reaction) of neutrons. In this case, eq.(4) holds with the appropriate replacements:

$$N_Z = \sum_A N(Z,A),\ \lambda_{\beta,Z} = \sum_A \lambda_\beta(Z,A)P_Z(A) \text{ and } P_Z(A) = N(Z,A)/N_Z. \qquad (6)$$

The isotopic abundance N(Z,A) can be obtained from the Boltzmann equilibrium conditions

$$\log[N(Z,A+1)/N(Z,A)] = \log[g(Z,A+1)/g(Z,A)] + \log[n_n]$$
$$-(3/2)\log[(A/A+1)T_9] + (5.04/T_9)S_n(Z,A+1) - 34.08, \qquad (7)$$

where g is the nuclear partition function, n_n is the neutron number density in cm^{-3}, T_9 is the temperature in 10^9 K, and S_n is the neutron separation energy in MeV. Equation (7) gives the distribution of N(Z,A) in A for a given Z. By setting the left-hand-side equal to zero and ignoring the small terms, its peak can be approximately located at the nucleus which has

$$S_n \simeq (T_9/5)(34-\log[n_n]). \qquad (8)$$

On the other hand, the nuclear mass formulae imply that the r-process path nuclei should have $S_n \sim 2$ MeV in order that the "observed" r-process abundance curve can be reproduced. Therefore, it may be said from eq.(8) that such conditions as $[n_n(cm^{-3}), T(K)] = [10^{24}, 10^9]$ and $[10^{32}, 5\times10^9]$ could be the candidates appropriate for the r-process. In general, the abundance $N_A = \sum_Z N(Z,A)$ can be obtained by solving eqs.(4), (6) and (7) with certain initial conditions (e.g. ^{56}Fe as the seed nucleus) and the estimated nuclear data such as $S_n(Z,A)$ and $\lambda_\beta(Z,A)$.

The classical static model of this sort has led the following findings: (i) the duration of the r-process is to be somewhat the order of few seconds or less. If it is too long, the fission product nuclei pile up too much; (ii) the "observed" abundances can not be explained with the one set of n_n and T values; (iii) the calculated abundance curve shows a strong even-odd effect stemming from the fact that S_n strongly depends on the even-oddness of the neutron number, which is in a sharp contrast to the rather smooth "observed" curve. This necessitates the inclusion of such effects as the β-delayed neutron emission after the freeze-out of the r-process.

Unfortunately, in contrast to the case of the s-process, such semi-empirical studies of the r-process could not succeed in restricting the astrophysical condition tight enough, mainly because of the lack of nuclear input data.

4.2. Stellar evolution and the r-process

The question as to in which stars (which stellar mass) and in which evolutionary stages the r-process indeed occurs remains open. Many candidates proposed so far include such a peculiar scenario as the collision of the neutron star and the black hole. Most scenarios starting with B^2FH, however, have dealt with the supernova explosion. Any realistic r-process calculations are extremely difficult since one has to deal with a few thousand unknown nuclei during the course of the dynamical stellar evolution.

The scenario once thought to be promising concerns the supernova explosion of stars with the mass of a few times 10 $M_{\odot}$. Around the end of the evolution, the gravitational collapse leads to a high-density ($\gtrsim 10^{10}$ gcm^{-3}) core, producing the highly-degenerate electrons with the high Fermi energy. As the result of the capture of these free electrons by hydrogen and heavy nuclei, much neutrons and neutron-rich nuclei appear near the periphery of the core according to the statistical equilibrium, which may be a good site for the r-process. The r-process calculation, coupled to the hydrodynamical treatment of the supernova, was performed in 1970's to show that the solar abundance curve could be well explained by one supernova explosion. However, the more recent studies of the supernova explosions tend to imply certain deficiencies in this scenario.

Many recent r-process studies have dealt with the supernova explosion passing through the outer He-burning shell which had finished the H-burning, which triggers the r-process with the neutron source due to the $^{22}Ne(\alpha,n)^{25}Mg$ reaction. Although this scenario could also reproduce the "observed" solar abundance curve pretty well, there are many difficulties such that it is far too premature to consider this as the final answer. One of the difficulties lies in the fact that the neutron density n_n is at most 10^{18} cm^{-3}, and therefore the presumption of the equilibrium between the n-capture and the n-emission does not necessarily hold. To remove this assumption requires the evaluation of the rates not only of the β-decay but of the n-capture, which is an extremely difficult task. In addition, some twists with respect to the initial conditions (such as the seed nuclear distribution) were necessary in order to obtain a good fit to the observed solar abundances. While these problems being unsolved, we decide here not to display the comparison of the theoretical and observational abundance curves.

Very recently, it has been speculated that the r-process might occur by the supernova explosion of ~ 9 $M_\odot$ stars. Up to now, no r-process calculations according to this scenario have been reported. The same holds for other more peculiar models for the r-process.

4.3. Neutron-rich nuclei and super-heavy elements

There are about six thousand nuclei expected in the region between the dashed lines in Fig.6, whose ground-states are stable against the neutron or proton emission. As of today, more than two thousand nuclei are known, and the number of new isotopes, mostly in the neutron-deficient side, is increasing thanks to the sophistication of the heavy-ion techniques. [Indeed, a few proton emitters have been found.] On the other hand, most of the neutron-rich nuclei which participate in the r-process remain unknown. In addition to the canonical way of producing neutron-rich nuclei by fissions in the reactor, the heavy-ion reactions have also been introduced, leaving some hope in the near future.

The beta-decay is very important in conjunction with the astrophysical time-scale as it determines the duration of the r-process. Various β-decay half-life calculations have been performed from both the macroscopic (statistical) and microscopic (nuclear shell mode) viewpoints. However, neither of these approaches can make highly reliable predictions for unknown nuclei as demonstrated in Fig.7. The same hold for the integrand function i.e. the β-strength functions, which are important in the r-process abundance calculations. A typical example concerns the β-delayed neutron emission in very neutron-rich nuclei, where the β-decay Q-value is much larger than the neutron separation energy in the daughter nucleus. The delayed neutron emission shifts the abundance curve to the direction of the lower mass number and at the same time decreases the even-odd effect (cf. Sec.4.1.). The experimental measurements of the strength function are much more difficult than those of the half-lives, but the data are slowly accumulating mainly for the fission product nuclei.

The neutron-capture rate is important in order to solve the r-process network correctly. This quest has been reinforced by the fact that the recent r-process models imply relatively low neutron density in contrast to the classical model in which the neutron capture rate did not explicitly appear in the calculation. Since the experiments on the radioactive isotopes are naturally difficult, we have to rely on theoretical predictions. Here, it is expected that the canonically used statistical (Hauser-Feshbach) model would not be appropriate for the very-neutron-rich nuclei since the nuclear level density would be very small there. A recent calculation has indeed shown the importance of the direct capture process. The unification of the statistical and direct-capture models is awaited.

The nuclear mass is required in the calculations of the β-decay Q-values and the neutron separation energies. In the past , many semi-empirical mass formulae have been proposed and applied. Judging from the comparisons of the predicted values and newly-observed data, however, the reliability of the predictions is not necessarily high.

The fission barrier is the another quantity needed in the r-process calculation, especially to know how high the atomic number the r-process can reach. It is also needed in the determination of the age of the Galaxy via U-Th chronometers and in the problem of the super-heavy element. For example, the importance of the β-delayed fission in these problems has been pointed out, where the evaluation of the fission barrier is of key importance in addition to the β-strength function. Usually, the deformed shell (Nilsson) model has been used. Again, the stability of the prediction is not too high as in the case of other quantities.

There are other miscellaneous quantities such as the energies and spins of the ground- and low-lying excited states, which are needed for precise r-process calculations. These data are of importance in the calculations of the n-capture cross section and the partition function, for instance. Because of the lack of presumedly more important data, these quantities have not been discussed in detail so far.

Another problem is related to the possible existence of the super-heavy element with Z ~ 110. Experimentally, the GSI (Darmstadt) group has recently produced the nucleus with Z=109. On the other hand, theoretical calculations have suggested that the half-lives of the super-heavy nuclei will be too short to survive the age of the solar system. In addition, the r-process calculations imply that the amount of the super-heavy elements would be extremely small, if at all, because the r-process path encounters the fissioning region before.

5. The age of the Galaxy

The nucleosynthesis in our Galaxy is supposed to have started ca. one billion years after the Big Bang. As is schematically shown in Fig.8, the synthesis continued for a long period (Δ), and at a short time (δ) after the last event the solar system solidified, that is, at ca 4.5 Gyr back from today.

If the nucleosynthesis rate is known as a function of time, Δ may be estimated by using the relative abundances of the long-lived isotopes. The classical examples of such nuclear clocks are ^{235}U (the half-life :7×10^8 yr), ^{238}U (4.5×10^9 yr) are ^{232}Th (1.4×10^{10} yr). The evaluation of δ may also be possible by adding ^{244}Pu which is known to have existed at the time of solar formation. In these studies, however, the calculation of the relative production ratios of those isotopes by the r-process is to be done in addition to the parameterization (e.g. by an exponential function) of the synthesis rate. The calculation of the production ratios are extremely difficult as much because of the imperfect r-process models as because of the lack of the input data (e.g. fission barriers) for the very neutron-rich heavy nuclei concerned.

The pair of the long-lived isotope ^{187}Re (4.3×10^{10} yr) and its β-decay daughter nucleus ^{187}Os is free from the above difficulties. This is because the r-process produces ^{187}Re directly but not ^{187}Os. The important point here is to evaluate the s-process contribution to the existing ^{187}Os in order to know the contribution due to the decay of ^{187}Re. In general, this has been done by using eq.(3) with the measured n-capture cross sections of ^{187}Os and of the s-process nucleus ^{186}Os, the former corrected for the possible effect of the first-excited state. [The first-excited state of ^{187}Os has the extremely low excitation energy. Therefore, the n-capture cross section at high temperatures might differ from the terrestrial (the ground-state) value.] In addition, the correction for the possible branching is to be considered, which may lead to an production of ^{187}Re by the s-process under certain conditions. While being free from the r-process models, the ^{187}Re-^{187}Os pair has a difficulty of being dependent on the s-process models.

The problem is furthermore complicated since the ^{187}Re β-decay half-life is expected to become very short at high temperatures in the stellar interiors. When a star forms out of the interstellar material, it contains ^{187}Re and ^{187}Os that had been produced in, and ejected from, the former generation stars. If such ^{187}Re feels high temperature during the astration in the new-born star and undergoes the fast β-decay, the relative abundance ratio ^{187}Re/^{187}Os may change until the re-ejection to the interstellar medium at the death of the star. Furthermore, ^{187}Os may meanwhile undergo the electron capture to become ^{187}Re. This ejected matter may also contain the ^{187}Re newly produced by the r-process. Indeed, a detailed calculation in consideration of these effects in conjunction with the chemical evolution of the Galaxy and the stellar evolution which depends on the stellar masses has been performed. The results has led to a pessimistic view that all the nuclear chronometers including Th-U can not yet be considered as reliable clocks. It is safe to say, however, that the duration of the nucleosynthesis Δ is 6 - 15 Gyr, and the time span between the last nucleosynthesis and the time of the solidification of the solar system δ is ca. 0.1 Gyr. The age of the Galaxy $\Delta+\delta+4.5$ Gyr gives the lower limit of the Universe. The above-mentioned value is in accordance with the ages determined by the Hubble constant and by the oldest globular cluster ever found within the various uncertainties.

The isotopic anormalies in meteorites have confirmed the existence of the short-lived isotopes such as ^{26}Al (7.2×10^5 yr) and ^{107}Pd (6.5×10^6 yr) at the time of the birth of the solar system and have led to the idea that there existed a last-minute "salting" to the solar material just prior to the formation of the solar system. For example, the s-process nucleus ^{205}Pb (1.5×10^7 yr) can be considered as one of such nuclear clocks which may give a hint as to the history of the early solar system.

6. Final remarks

In this article, we have summarized the idea of the nucleosynthesis due to the s- and r- processes. In both cases, there remains much uncertainties regarding the astrophysical sites. Speaking of the r-process, it is necessary to improve the nuclear input data for the very neutron-rich nuclei while the search for the astrophysical site(s) is in chaos.

The most part of this article heavily relies on the pioneering works done by W.A.Fowler, A.G.W.Cameron, D.D.Clayton and others. It should be noted here, however, that it inevitably contains the bias which the present write has

nourished through the collaborations with many colleagues including M.Arnould, E.R.Hilf, W.Hillebrandt, W.M.Howard, T.Kodama, G.J.Mathews, M.Yamada, K.Yokoi and R.A.Ward.

Finally, the author should like to dedicate this to M.Yamada on the occasion of his 60th birthday.

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7. References

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*) The age of the Galaxy is discussed in the above-mentioned review by D.N.Schramm. The complexities of the problem are discussed in detail by: K.Yokoi, K.Takahashi and M.Arnould 117 (1983) 65, which may not suit for optimistic readers however.

Figure Captions

Fig.1 Observed abundances in the solar system (per 10^6 Si atoms). The values for Th and U are for 4.5 Gyr ago. The heavy nuclei except ^{50}V, ^{138}La and ^{180}Ta can be explained as the result of the nucleosynthesis in the stellar interiors. The data are based on E.Anders and M.Ebihara, Geochim.Cosmochim. Acta 46 (1982) 2263.

Fig.2 a) the s- and r- process paths, assuming the seed nucleus ^{56}Fe; b)Examples of heavy nuclides produced by the s-, r- and p- processes. A is the mass number.

Fig.3 Qualitative decomposition of the solar abundances into the s-, r- and p- process contributions, based on A.G.W.Cameron, in "Essays in Nuclear Astrophysics" (1982, Cambridge Univ. Press), p.23.

Fig.4 σN_A product for the s-only nuclei (σ: neutron-capture cross section, N_A: solar abundance). The curve is obtained by an interpolation by assuming the exponential distribution for the neutron flux τ, based on P.A.Seeger, W.A.Fowler and D.D.Clayton, Astrophys.J.Suppl. 97 (1965) 121.

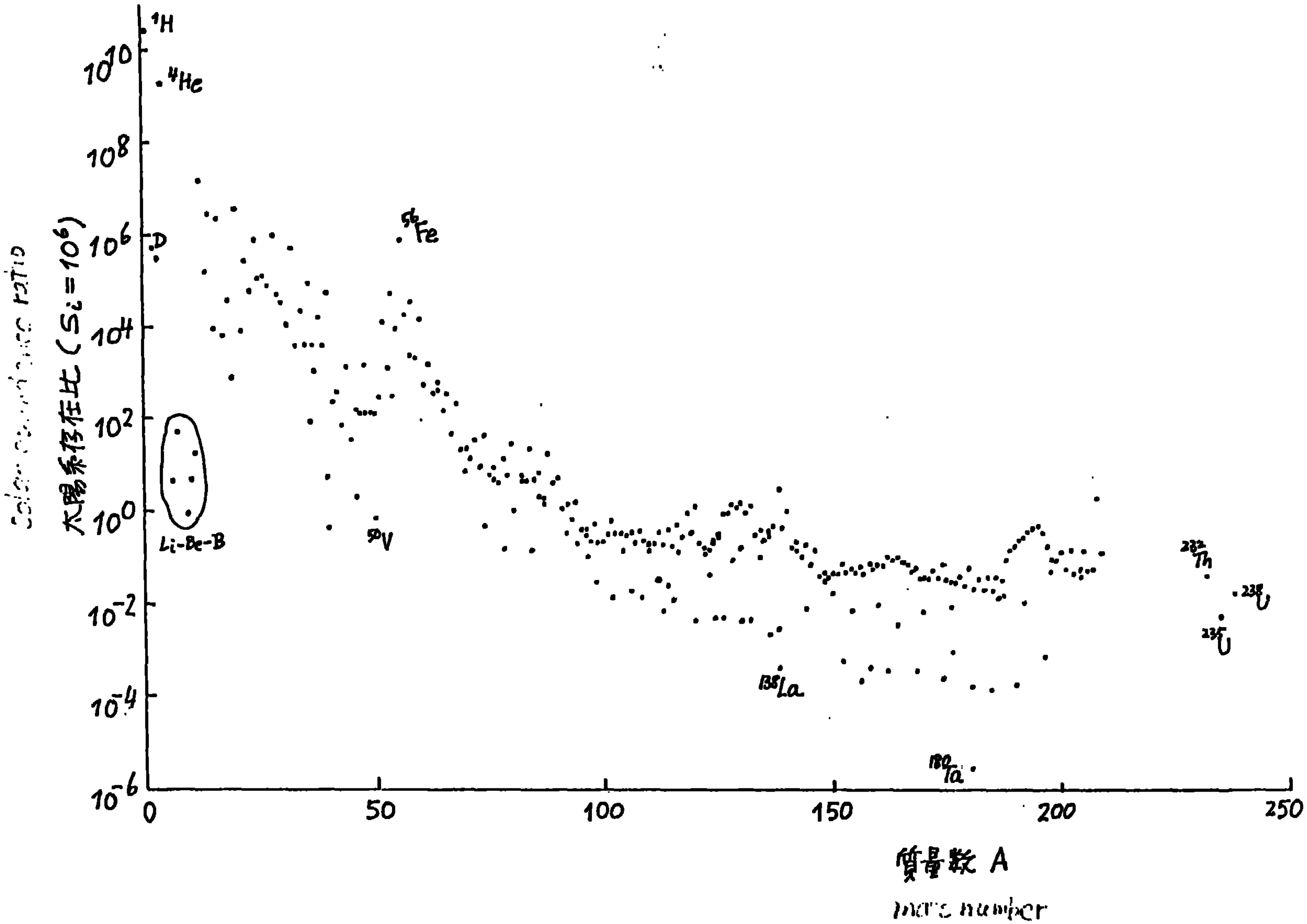
Fig.5 Example of the "observed" r-process abundances in the solar system, based on B.J.Allen, J.H.Gibbons and R.L.Macklin, Adv.Nucl.Phys. 4 (1971) 205.

Fig.6 r-process path on the N-Z-plane, assuming the seed nucleus ^{56}Fe. At the corner corresponding to the mass number A=80, 130 and 194, the β-decays are slow, resulting in the three peaks seen in the abundance curve. The actual locations of the neutron and protton drip lines depend on the even-oddness of the particle number, which is not shown in this qualitative figure. Also, the r-process path shown here is quite qualitative,

Fig.7 Experimental β-decay half-lives for newly-found isotopes compared with theoretical predictions. The closed circles are the predictions from the gross theory: K.Takahashi, M.Yamada and T.Kondoh, Atm.Nucl.Dat.Tables 12 (1973) 101, and the open circles are the values from the shell-model calculation: H.V.Klapdor, J.Metzinger and T.Oda, Atm.Nucl.Dat.Tables 31 (1984) 81. The analysis is based on the work by E.Roeckl et al. at GSI, Dramstadt.

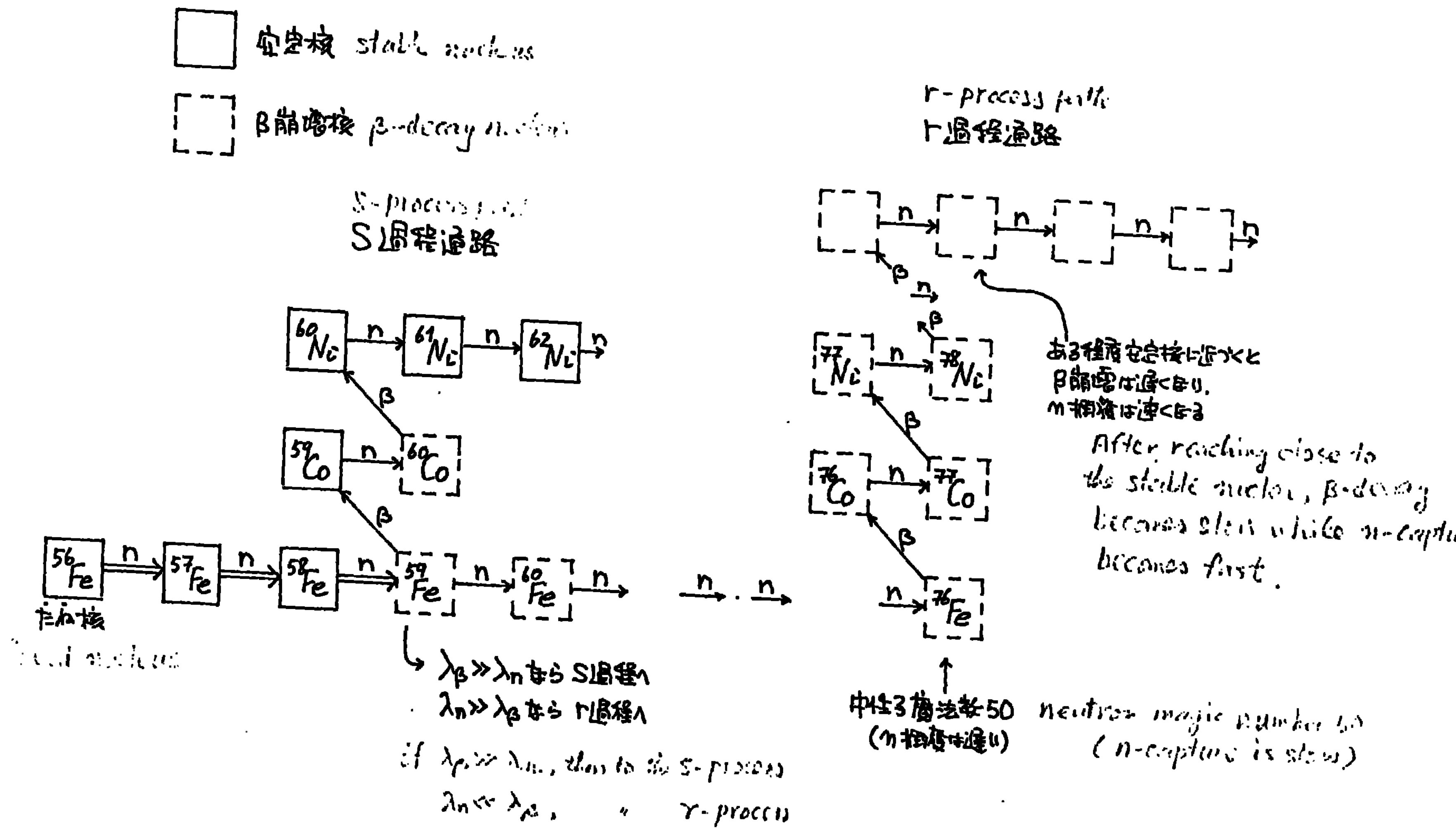
Fig.8 Schematic illustration of the nucleosynthesis rate in our Galaxy as a function of time, based on W.A.Fowler, Proc.The Robert A.Welch Foundation Conf. on Chemical Research XXI (1977, Houston) p.61.

Fig. 1
図1



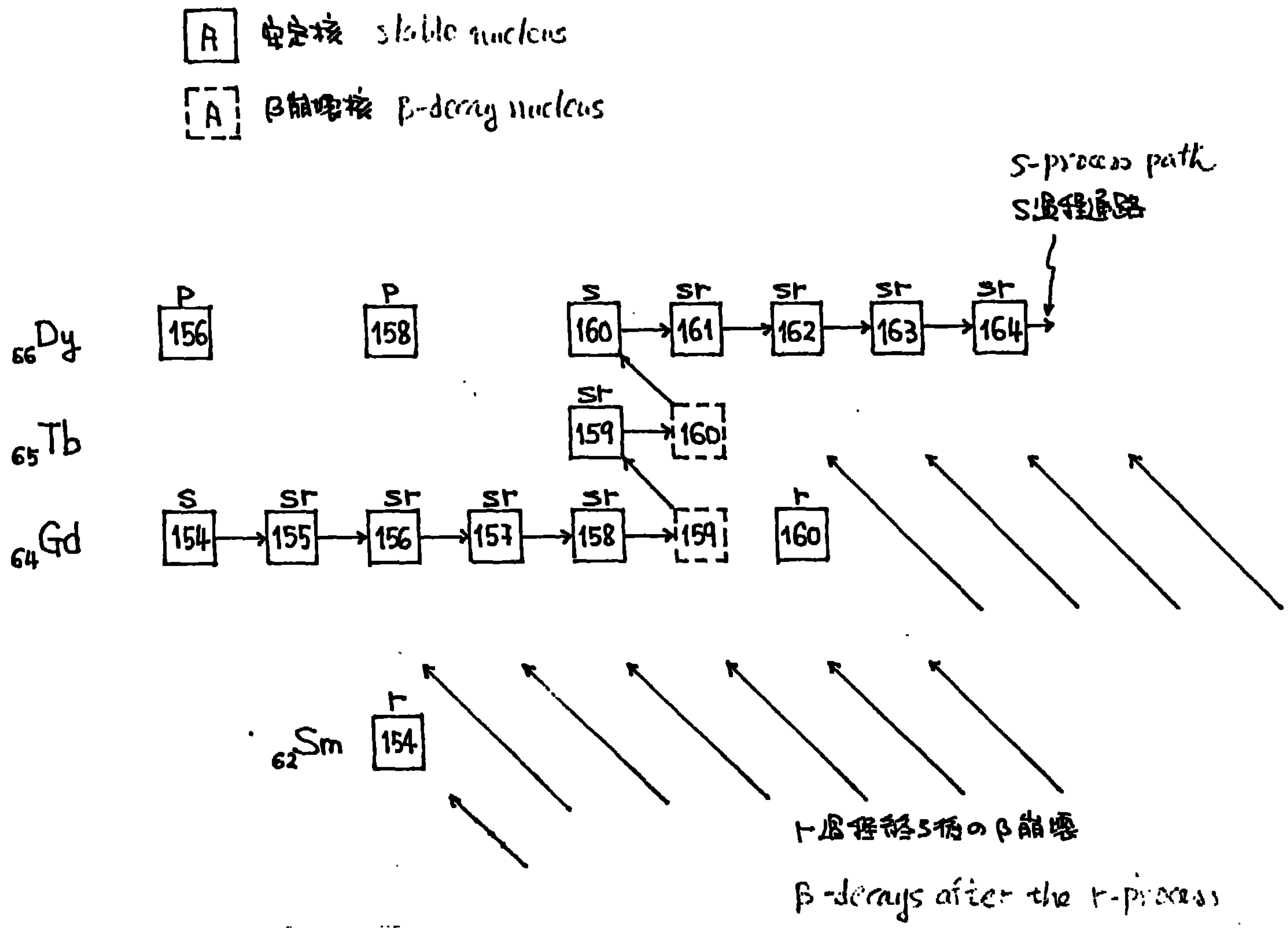
^{1}H
^{4}He
D
^{56}Fe
Li-Be-B
^{50}V
^{138}La
^{180}Ta
^{232}Th
^{238}U
^{235}U
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
0
50
100
150
200
250
太陽系存在比 (Si = 10^6)
Solar abundance ratio
質量数 A
mass number

Fig. ...
図2a



安定核 stable nucleus
β崩壊核 β-decay nucleus
S過程通路
r-process path
r過程通路
60Ni
61Ni
62Ni
59Co
60Co
56Fe
57Fe
58Fe
59Fe
60Fe
たね核
77Ni
78Ni
76Co
77Co
76Fe
n
β
$\lambda_\beta \gg \lambda_n$ ならS過程へ
$\lambda_n \gg \lambda_\beta$ ならr過程へ
r-process
ある程度安定核に近づくと
β崩壊は遅くなり、
n捕獲は速くなる
After reaching close to
the stable nuclei, β-decay
becomes slow while n-capture
becomes fast.
中性子魔法数50
(n捕獲は遅い)
neutron magic number 50
(n-capture is slow)

Fig. 2b
図2b



A 安定核 stable nucleus
A β崩壊核 β-decay nucleus
s-process path
s過程通路
p p s sr sr sr sr
$_{66}$Dy 156 158 160 161 162 163 164
sr
$_{65}$Tb 159 160
s sr sr sr sr r
$_{64}$Gd 154 155 156 157 158 159 160
r
$_{62}$Sm 154
r過程終了後のβ崩壊
β-decays after the r-process

Fig. 3
図3

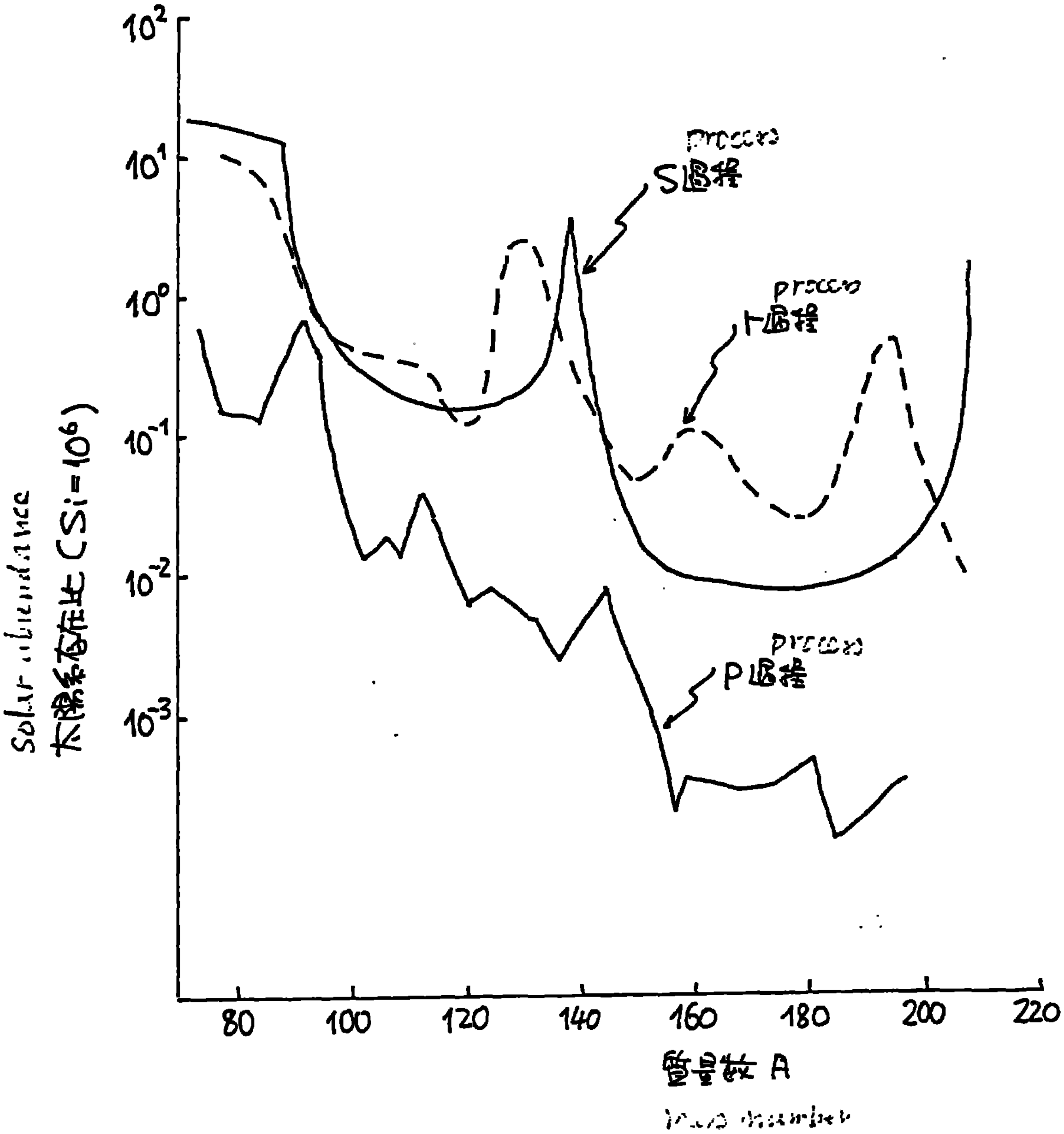
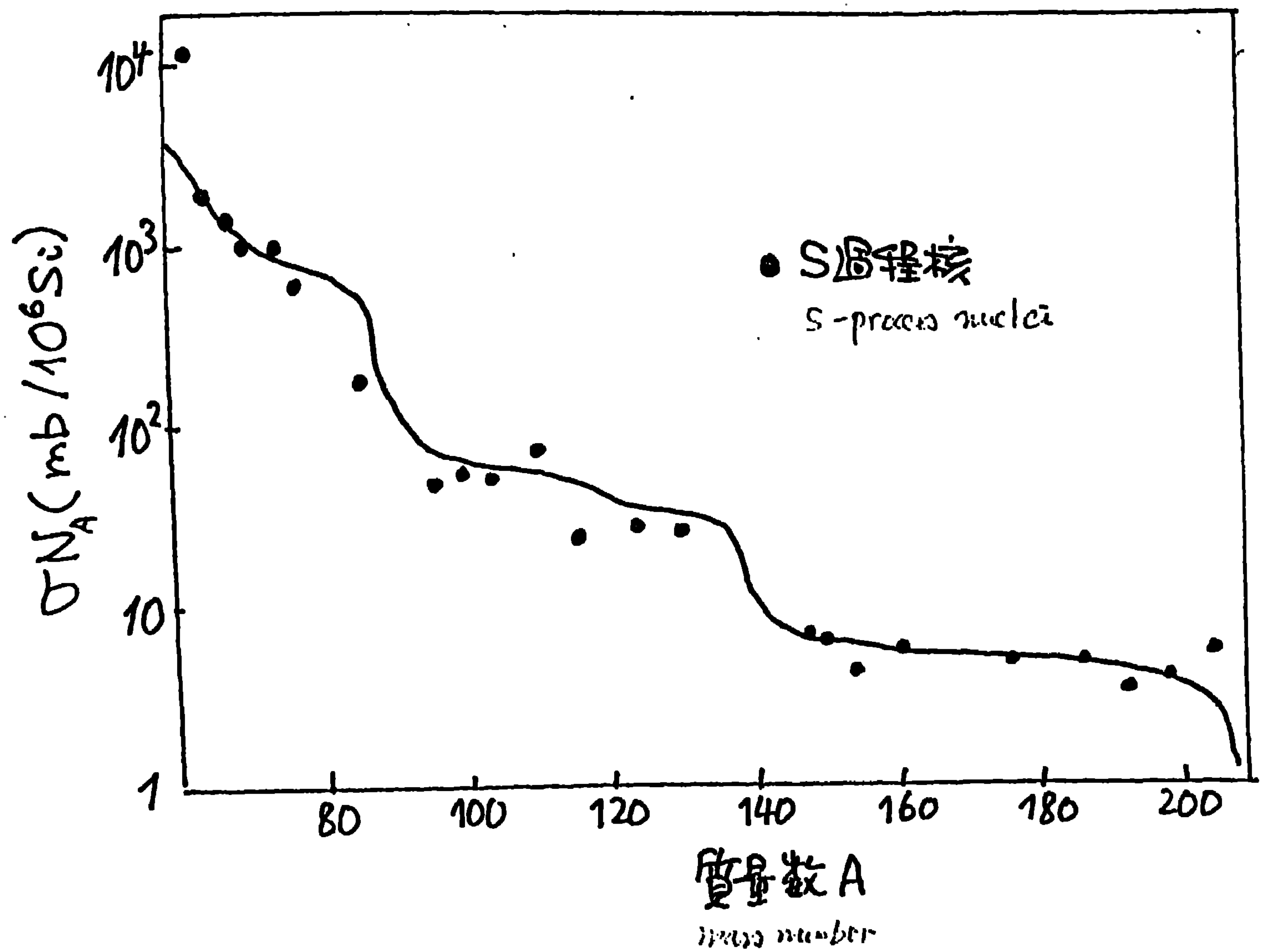

Solar abundance
太陽系存在比 (Si=10^6)
10^2
10^1
10^0
10^-1
10^-2
10^-3
process
S過程
process
r過程
process
P過程
80
100
120
140
160
180
200
220
質量数 A
Mass number

Fig. 6



S過程核
S-process nuclei
10^4
10^3
10^2
10
1
80
100
120
140
160
180
200
σN_A (mb / 10^6 Si)
質量数 A
mass number

Fig 5

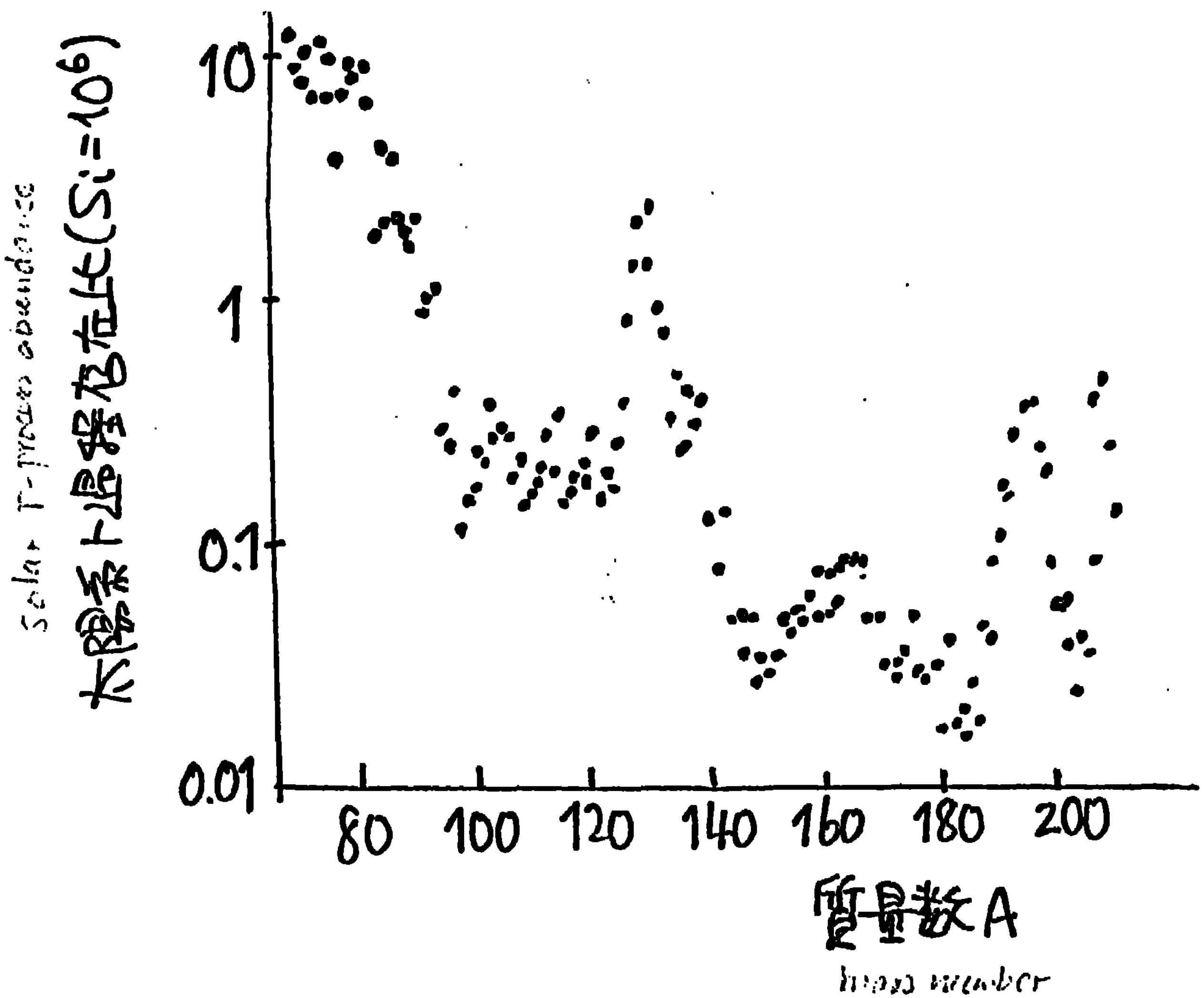
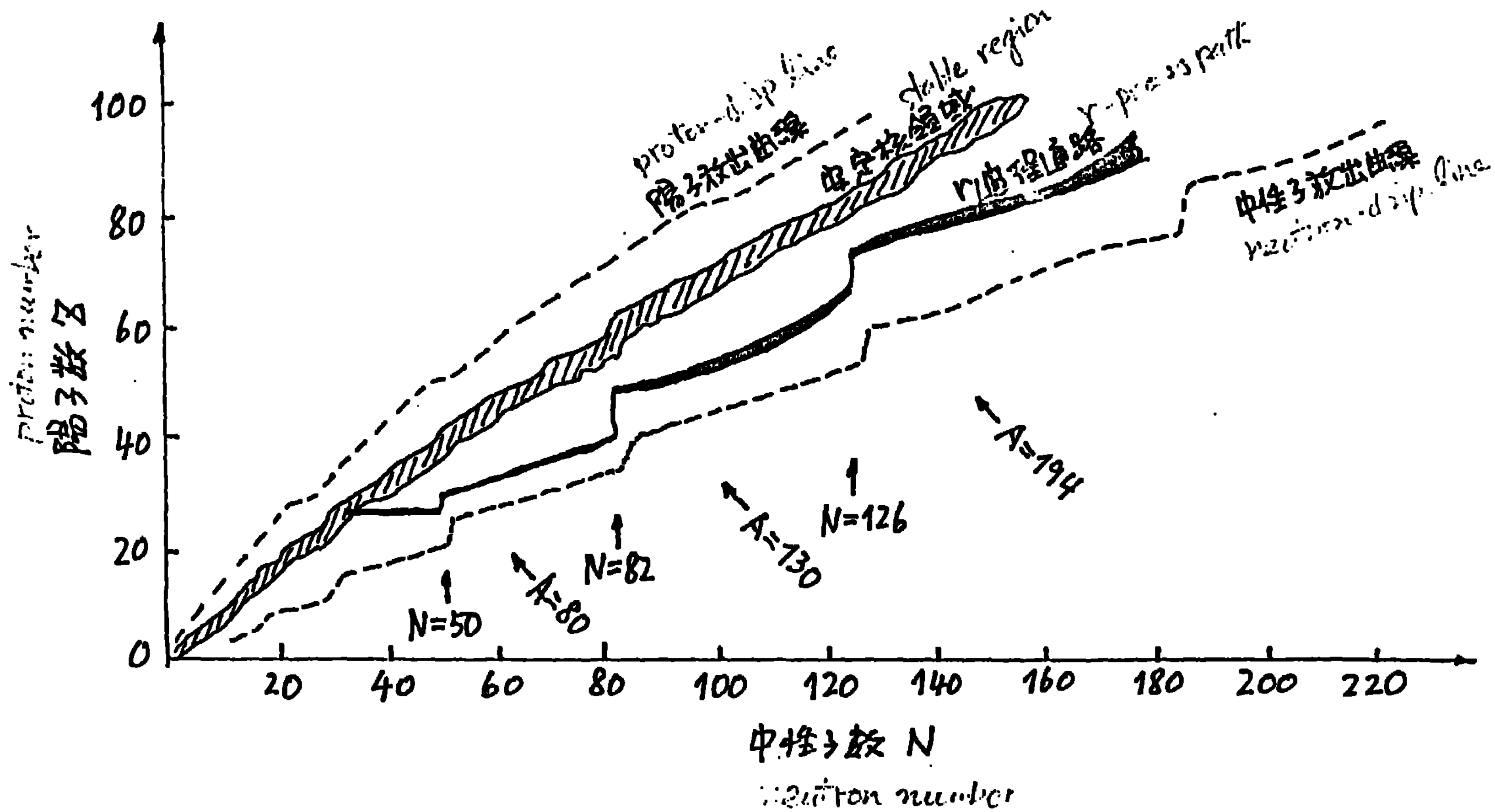

10
1
0.1
0.01
80
100
120
140
160
180
200
太陽系r過程存在比(Si=10⁶)
Solar r-process abundance
質量数A
mass number

図6
Fig.6



陽子放出曲線
中性子放出曲線
安定核領域
stable region
r過程通路
中性子数 N
陽子数 Z
N=50
N=82
N=126
A=80
A=130
A=194
0
20
40
60
80
100
120
140
160
180
200
220

Fig.7

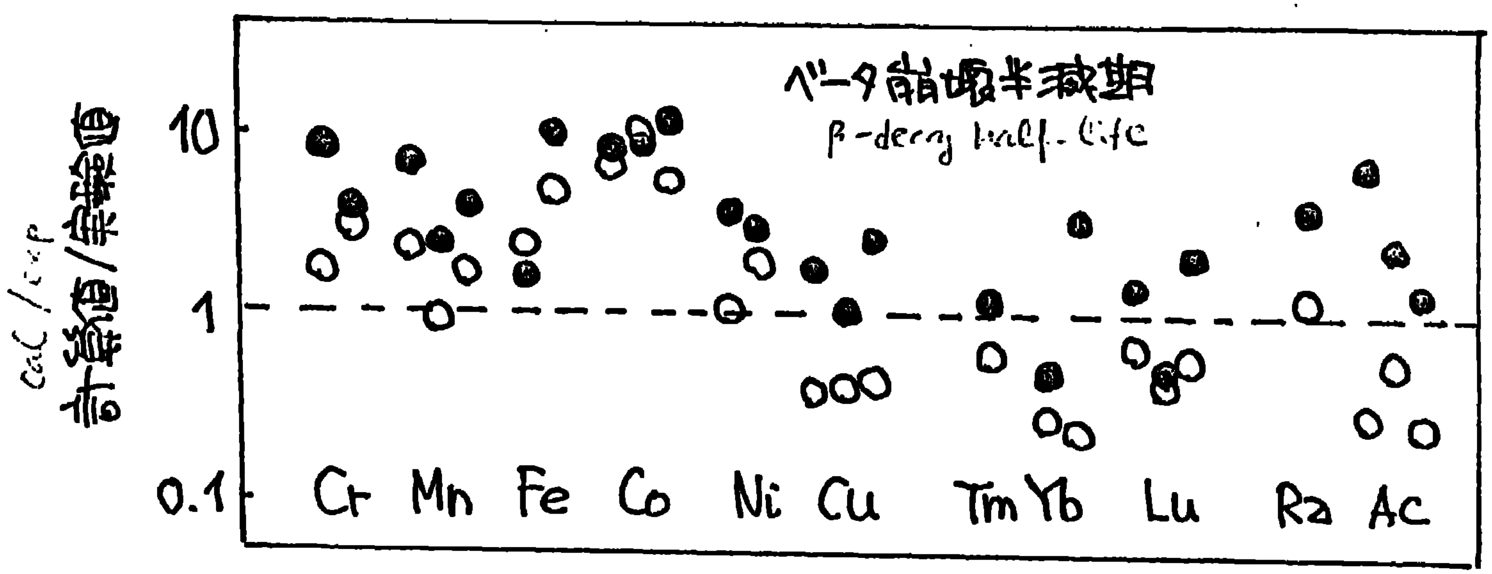
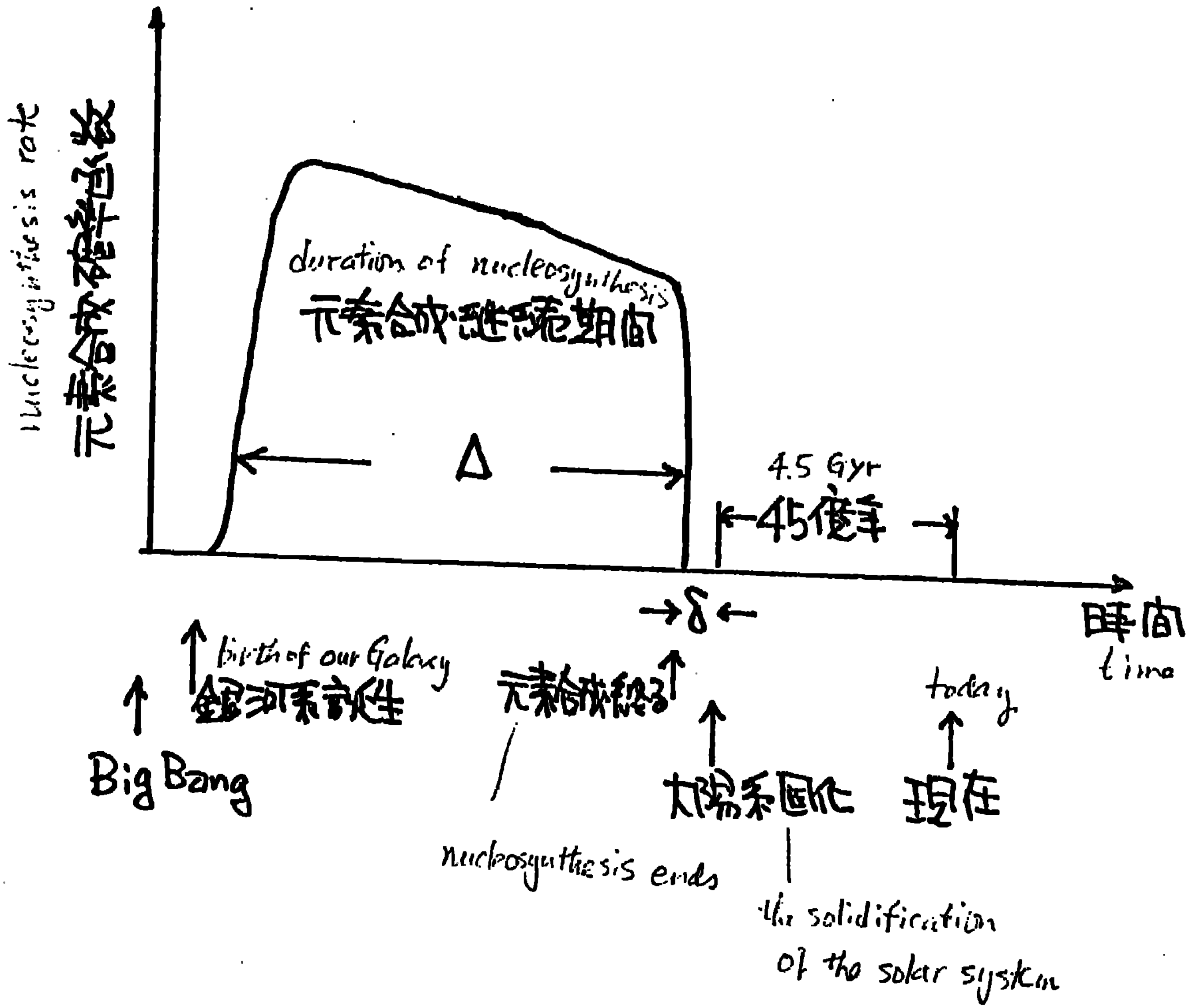

ベータ崩壊半減期
β-decay half-life
計算値/実験値
cal/exp
10
1
0.1
Cr
Mn
Fe
Co
Ni
Cu
Tm
Yb
Lu
Ra
Ac

Fig.8



元素合成速度
nucleosynthesis rate
duration of nucleosynthesis
元素合成継続期間
Δ
4.5 Gyr
45億年
δ
時間
time
birth of our Galaxy
銀河系誕生
元素合成終る
Big Bang
nucleosynthesis ends
太陽系固化
the solidification of the solar system
today
現在